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A review on configurations, control and sizing methodologies of hybrid energy systems

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ABSTRACT

The demand of energy is increasing at an escalating pace and cannot be fulfilled entirely by conventional energy systems, due to their limited supplies. In addition to this they have a radical impact on the environment. In comparison to them hybrid energy systems are a suitable combination of renewable and non-renewable energy systems which keeps into account the advantages of both these systems, thus able to achieve reduction in cost of implementation and maintenance of the system, limited emission levels, improvement in reliability of the overall system etc. Designing of hybrid energy system for a locality and its implementation is an uphill task as the input parameters of the sources considered are randomly varying with time and are also independent of the load requirements. The paper encompasses review on various important sectors needed to be considered while designing and implementation of hybrid energy system; this includes configurations, criteria selection, sizing methodologies and control & energy management. This will help the designer to use suitable design constraints required while implementing hybrid energy system for grid connected or in off grid modes as per the requirement of the locality.

Contents

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1. Introduction

The need of energy is increasing rapidly due to fast urbanization and industrialization in the developed and developing nations. The prevailing energy demand is heavily dependent on fossil fuels [1–3] which are not only limited and inadequately distributed on the earth's crust [4,5] but are also associated with serious environmental problems [5–7]. On the other hand electricity in cleanest form is generated by the renewable energy sources [8,9], which are readily available in nature and are inexhaustible. But they also have various drawbacks, such as overdependence on environmental conditions, which varies from place to place and hence can lead to designing flows. The system thus developed for a particular application may be found to be oversized or undersized. This makes the problem difficult to solve as the fluctuating source may not be able to supply the demand at some critical conditions [7,10–12]. These situations have led us to a significant increase in the number of scientific publications [13] on the field of renewable energy over the last few decades. The energy produced by the renewable energy systems has been increased due to improvement in technology and awareness among the people, around the world. In India a large portion of population lives in rural and remote areas which are present far away from grid supply and a heavy cost is involved in extending the grid. Therefore such areas can be electrified in decentralized mode by renewable energy plants such as small hydro, biomass, solar, wind, etc. and their combination in integrated manner. As per the rural electrification act 2003, the remote rural areas can be electrified by renewable energy systems, apart from electrification of individual household by renewable energy, the integrated renewable energy system (IRES) and the hybrid energy system (HES) [14] can also be developed to supply the people. HES or IRES requires the knowledge of parameters like existing technologies, available government policies, customer requirement and resource limitations [15]. The present paper will restrict to the development of HES for a specific application depending on the type of load, design constraints and sizing methodology. This will help the system designers to increase efficiency and reliability of the overall system [5,7, 16,17]. Various control strategies are also discussed, which will be suitable for proper running of the plant. Section 2 offers a study comprising various HES architectures which can be selected, depending on the need of the consumer. Section 3 explains various design constraints, which may be considered, while sizing of the system. They can be categorized into technological, economic, socio-political and environmental factors. Section 4 includes data generation methods required by different sizing methodologies while sizing of an HES. The section also covers a review of various methodologies used during sizing of HES [18]. After designing of the system, proper controlling technique is required for smooth operation of the plant, so different control configuration is also studied in Section 5. Finally, Section 6 draws the future scope with conclusion in Section 7.

2. Hybrid energy system configurations

The basic components of the hybrid energy systems mainly comprise renewable energy generators (AC/DC sources), non-renewable generators (AC/DC sources), power conditioning unit, storage, load (AC/DC) and sometimes may include grid. A general hybrid energy system configuration has been depicted in Fig. 1 as shown below.

The various configurations are listed in Table 1, which can be further summarized into DC coupled, power frequency AC coupled, high frequency AC coupled and hybrid coupled system (comprising of both AC and DC bus) [19–26]. The selection of a particular configuration depends on the type of application which is listed in Table 1.

3. Evaluation criteria for HES

Selection of evaluation criteria is one of the important works necessary for designing HES for a required locality given in [27]. Beceali et al. [28] used ELECTRE for assessing an action plan to diffuse renewable energy technologies at regional level. Goletsis et al. [29] explored the energy planning approachfor ranking the projects. Topcu and Ulengin [30] analyzed the possible energy alternatives depending on their physical, environmental, economical, political and other uncontrollable aspects. Ribeiro et al. [31] developed a multi-criteria decision analysis (MCDA) tool to allow ranking of different scenarios relying on their performance on 13 criteria covering economic, job market, quality of life of local populations, technical and environmental issues. Various criteria

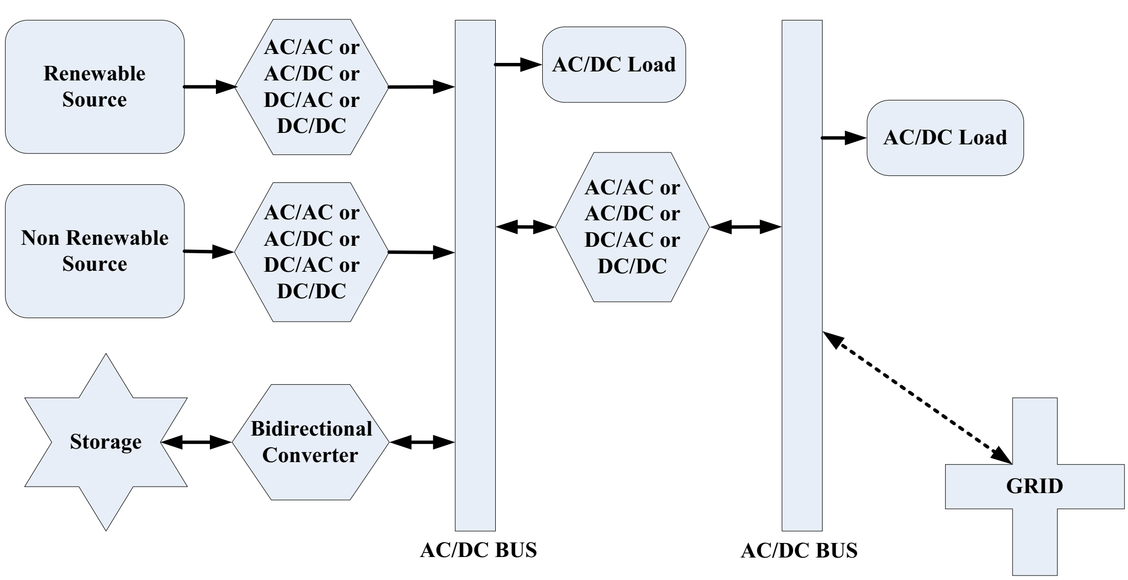

Fig. 1. Basic components of HES.

Table 1
Configuration of HES.

Configurations	Sources	Loads	Advantages	Drawbacks	Applications	References
DC coupled system	DC	DC	Synchronization is not needed	The configuration consists of a single inverter and hence if the inverter is out of service, then the system will be unable to fulfill the load requirements	Low voltage DC microgrid	[19]
Power frequency AC coupled system	AC	AC	Protection is easier	Coupling indicators may be required to achieve Desired power flow management	AC microgrid	[23,24]
High frequency AC coupled system	AC at various frequency	HFAC	High efficiency of the system with reduced size and weight of the heat dissipation components	High frequency power converters have high switching losses resulted due to high switching rates	Aeroplanes, vessels, submarines and space station applications	[25,26]
Hybrid coupled system	AC and DC	AC and DC	As the system is most flexible compared to other configurations, so a system can be designed with highest efficiency and at a reduced cost	Control and energy management can be difficult as it requires the presence of both AC and DC loads	Power sources and Loads are both AC and DC	[18]

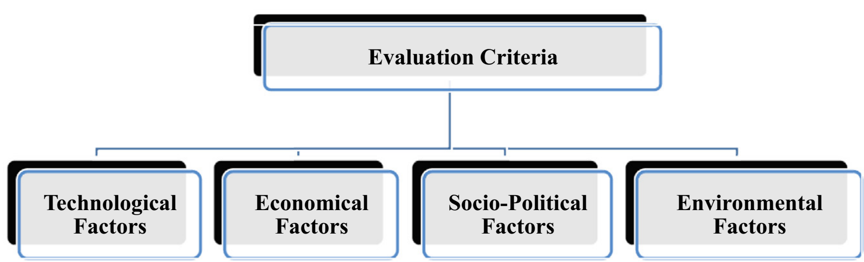

Fig. 2. Factors impacting the selection of the renewable energy system.

involved in designing of HES are shown in Fig. 2 obtained by taking into account the above work and are given in Table 2.

Table 2 explains the factors involved while designing a hybrid energy system, their purpose and parameters in which they depend.

Some of these criterions are broadly explained using mathematical formulation in the following section; this includes some of the technological, economic, socio-political and environmental factors. Rubio et al. [32] explained various parameters along with other parameters which can be considered while sizing a hybrid energy system. Along with them some more parameters are also covered in great detail.

3.1. Hybrid energy system design parameters

Performance parameters are used for the determination of reliability & feasibility and also help the system designer to design an appropriate system suitable for a given application. Some of these parameters are described below.

3.1.1. Technological factors

3.1.1.1. Loss of power supply probability. As the solar and wind parameters values are random and intermittent in nature, the determination of the reliability of the system becomes an important consideration. One of the parameters that helps us to access the system's reliability is loss of power supply probability (LPSP) [33,34]. It is defined as the ratio of the total energy deficit to the total demand during the considered period.

$$\mathrm{LPSP} = \frac{\sum_{t=1}^{T} \mathrm{DE}(t)}{\sum_{t=1}^{T} P_{\mathrm{load}}(t)\Delta t}$$

3.1.1.2. Equivalent loss factor. Equivalent loss factor (ELF) is the ratio of effective load outage hours to the total number of hours. It contains the information about both the number and magnitude of outages. In the remote rural areas a standalone system with ELF < 0.01 is acceptable. Electricity suppliers aim at 0.0001 in the developed countries [35,36].

$$\mathrm{ELF} = \frac{1}{\mathrm{H}} \sum_{n=1}^{H} \frac{E(Q(h))}{D(h)}$$

Where $Q(h)$ and $D(h)$ are the amount of load that is not satisfied and demand power in hth step, and H is the number of time steps.

3.1.1.3. Loss of load expected. Loss of load expected (LOLE) or expected energy not supplied is the energy that will not be supplied under the conditions when load exceeds generation.

$$\mathrm{LOLE} = \sum_{h=1}^{H} E[\mathrm{LOL}(h)]$$

Where, $E[\mathrm{LOL}(h)]$ is the expected value of loss of load at hth time step:

$$E[\mathrm{LOL}] = \sum_{s \in S} T(s) \times f(s)$$

$f(s)$ is the probability of meeting state s and $T(s)$ is the loss of load duration, given that the occurring state s and S is the set of all the possible states.

3.1.1.4. Total energy lost. The total energy lost (TEL) due to extra power generation (PGS) from HES is minimized by imposing the regulation that such a quantity should not exceed a specific threshold over a defined analyzed period T, which is assumed according to [37]to be 8760 h (1 year). The following equations

Table 2
Evaluating Criterions for designing HES.

S No	Criterion	Purpose/scope for criterion	Measurable parameters
1	**Technological factors**		
	• Feasibility	• Ensure the possibility of implementing HES	• Validating the results regularly
	• Risk	• Ensure the possibility of implementing HES by calculating the number of problems associated during failures while testing of the system	• Number of problems experienced while encountering failures in a tested system
	• Reliability	• The criterion estimates the technology of HES implemented. HES can be tested in laboratory or can be performed in the pilot plants, or it could be still improved before implementing during simulation, considering various parameters	• The effectiveness of the system for serving a variable load in accordance with time
	• The duration of preparation phase	• The criterion calculates the availability of the renewable energy potential in the locality, alternative to decrease the financial assets and reach the minimum cost	• The cost of the implementation phase is judgment by taking into accounts years or months of implementation
	• The duration of implementation phase	• The criterion evaluates the applicability of HES alternative to reach the minimum cost	• The cost of the implementation phase is judgment by taking into accounts years or months of implementation
	• Community and predictability of performance	• This criterion evaluates the operation and performance of the HES	• It is important to know if the technology operates continuously and confidently
	• Local technical know how	• This criterion includes the evaluation which is based on a qualitative comparison between the complexity of the considered technology and the capacity of the local actors	• It ensures an appropriate operating support for maintenance and installation of technology for renewable energy alternative
2	**Economic factors**		
	• Implementation cost	• This criterion analyzes the total cost of the energy investment in order to be fully operational	• Total cost of the system
	• Availability of funds	• This criterion evaluates the national and international sources of funds, and economic support of government	• Various factors present in a country or organization
	• Economic value (PW, IRR, B/C)	• This criterion judges the proposed renewable energy alternative as economically	• It uses engineering economics techniques which are present worth (PW), internal rate of return (IRR), benefit/cost analysis (B/C), and payback period (PP)
3	**Socio political factors**		
	• Compatibility with the national energy policy objectives	• The criterion analyses the integration of the national energy policy and the suggested renewable energy alternative	• It measures the degree of objectives' convergence between the government policy and the suggested policy. The criterion also takes into account the government's support, the tendency of institutional actors, and the policy of public information
	• Political acceptance	• The criterion searches whether or not a consensus among leader's opinions for proposed renewable energy alternative exists. Also it takes into account avoiding the reactions of the politicians and satisfying political leaders	• Policy implementation
	• Social acceptance	• The criterion enhances consensus among social partners. Also it takes into account avoiding the reactions from special interest special groups for renewable energy alternatives	• Public participation
	• Labor impact	• Renewable energy alternatives are evaluated taking into account labor impact	• It is related to direct and indirect employments and the possible indirect creation of new professional figures are also assessed
4	**Environmental factors**		
	• Pollutant emission	• The criterion measures the equivalent emissions of CO_2, air emissions which are the results of the combustion process, liquid wastes which are related to secondary products by fumes treatment or with process water, and solid wastes	• The evaluation of the criterion includes type and quantity of emissions, and costs associated with wastes treatments. Also, the electro-magnetic interferences, bad smells, and microclimatic changes for energy investments are taken into account in the evaluation of this criterion
	• Land requirement	• Land requirement is one of the most critical factors for energy investment	• A strong demand for land can also determine the energy losses
	• Need of waste disposal	• The criterion evaluates the renewable energy's damage on the quality of the environment	• The renewable energy alternative can be evaluated to reduce damage on the quality of life and to increase the sustainability by taking into account this criterion

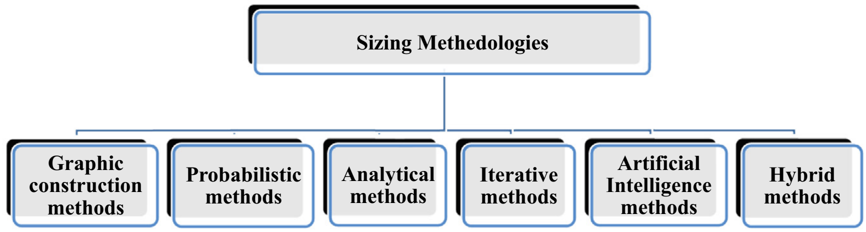

Fig. 3. Methodologies used for sizing of HES.

impose this constraint:

$$\mathrm{TEL} = \begin{cases} \sum_{t=1}^{T} (E_{\mathrm{PGS}}(t) - \mathrm{LD}(t)), & \text{if } \mathrm{LD}(t) < E_{\mathrm{PGS}}(t) \\ 0 & \text{else} \end{cases}$$

$$0 < \mathrm{TEL} \le \mathrm{THR}$$

Where E_{PGS} is the energy generated by PGS and LD is the load demand. The total energy lost due to extra generated power is sold to the grid according to the adopted system energy management strategy.

3.1.1.5. Level of autonomy. Level of autonomy (LA) is defined as one minus the ratio of the total number of hours in which loss of load (LOL) occurs and the total number of hours of operation.

$$\mathrm{LA} = 1 - \frac{H_{LOL}}{H_{tot}}$$

where H_{tot} is the total number of hours for which the system is working and H_{LOL} is the number of hours for which loss of load occurs [38].

3.1.1.6. Battery state of charge. State of charge (SOC) in the batteries is related to the energy stored in a system, it can be calculated as follows [39]:

$$\mathrm{SOC}(t+1) = \mathrm{SOC}(t)\sigma + I_{\mathrm{bat}}(t)\Delta t \eta(I_{\mathrm{bat}}(t))$$

where σ is the self-discharging rate of battery bank, $I_{\mathrm{bat}}(t)$ is the batteries charging current, Δt is the sampling period, and $\eta(I_{\mathrm{bat}}(t))$ is the charging current efficiency. SOC can help the designer to select a battery with a definite storage capacity ensuring the constraints must be satisfied [40–42].

3.1.2. Economic factors

3.1.2.1. Levelized cost of energy. Levelized cost of energy (LCE) can be explained as the ratio of the total yearly cost of the system to the yearly electricity sent by the system, which can be evaluated as given below [43,44]

$$\mathrm{LCE} = \frac{\mathrm{TAC}}{E_{\mathrm{tot}}}$$

TAC represents the total annualized cost, and E_{tot} the annual total energy.

3.1.2.2. Capital recovery factor. The capital recovery factor (CRF) can be interpreted as [44] the amount of equal (or uniform) costs to be received for t years such that the total present value of all these equal costs is equivalent to a payment of one rupee at present, if interest rate is d.

$$\mathrm{CRF} = \frac{d(1+d)^t}{(1+d)^t - 1}$$

Here d is the discount rate and t is the time in years for the plant in operation.

3.1.2.3. Long term cost of the hybrid energy system. Long term capital cost (C_n) of the system can be calculated as the sum of first installation cost, maintenance and operation cost and replacement cost [45].

$$C_n = \mathrm{IC}_0\left[(1-\gamma) + mx\frac{x^n-1}{x-1} + \frac{c_0 M_f}{\mathrm{IC}_0} y \frac{y^n-1}{y-1} + \Psi\right]$$

where, the first component is the initial capital cost, as here γ is the subsidy given by the state which is followed by the maintenance & operation cost and replacement cost (Ψ).

3.1.2.4. Average generation cost of energy. It is the average generation cost of energy (C_{av}) of all the devices included in the system design [46].

$$C_{\mathrm{av}} = \frac{\{(r(1+r)^n + m)/((1+r)^n - 1)\}\sum_i P_i R_i}{(87.6)\sum_i R_i K_i}$$

where, C_{av} is the average cost (Rs/kWh),

3.1.2.5. Net present value. Net present value (NPV) can be evaluated by adding the present discount values of the incomes while subtracting the discounted present costs through the useful lifetime of the system [41].

$$\mathrm{NPV} = \sum \mathrm{NPV}_{\mathrm{sale\_i}} + \sum \mathrm{NPV}_{\mathrm{end\_i}} - \mathrm{C}_{\mathrm{investment}} - \sum \mathrm{NPV}_{\mathrm{r\_i}} - \sum \mathrm{NPV}_{\mathrm{O\&M\_i}}$$

where $\mathrm{NPV}_{\mathrm{sale\_i}}$ are the present discounted values of income from the sale i (e.g. electrical energy sold to the grid), $\mathrm{NPV}_{\mathrm{end\_i}}$ are the present discounted values of incomes from the residual value of component at the end of the lifetime of the HES, $C_{\mathrm{investment}}$ is the initial total investment cost, $\mathrm{NPV}_{\mathrm{r\_i}}$ are the present discounted cost of future costs of replacing the components throughout the life of the system, $\mathrm{NPV}_{\mathrm{O\&M\_i}}$ are the discounted present costs of future costs of operation and maintenance of component i throughout the life of the system.

3.1.2.6. Annualized cost of system. The annualized cost of system (ACS) is composed of the annualized capital cost, annualized maintenance cost (C_{amain}) and the annualized replacement cost (C_{arep}) [34].

$$\mathrm{ACS} = C_{\mathrm{acap}} + C_{\mathrm{amain}} + C_{\mathrm{arep}}$$

3.1.2.7. Fuel consumption. This objective minimizes the total amount of energy consumption by non-renewable plants as given in [47,48]:

$$FC = \sum_{t \epsilon T} \sum_{j \epsilon F} \omega_t b_{jt} y_{jt}$$

Here ω is the discount factor, b_{jt} cost of imported fuel of type j in time period t ($/unit) and y_{jt} is the amount of imported fuels of type j in time period t (units).

3.1.3. Socio-political factors

3.1.3.1. Social acceptance. Social acceptability (SA) is included as social performance evaluation criteria in order to take into consideration the social resistance to the installation of HES. In this context, land use and visual impact have been included as social negative effects, as well as electromagnetic interferences, acoustic noise, shadow flicker, and eco-system disturbance [49]. In [37] the social criteria technique is performed by using a fuzzy logic algorithm, where the land used area of power generation system and the number of required WT are the input variables, while the output of this algorithm is a social acceptance indicator. Stigka et al. [50] presented a literature review addressing the public acceptance of renewable energy as a replacement for fossil fuels in electricity production.

3.1.3.2. Portfolio risk. This objective seeks to minimize the exposure to fuel price instability for carrying out socio-political decisions [47,48,51].

$$\mathrm{PR} = \sum_{t\epsilon T}\left[\sum_{j\epsilon F}\alpha_{jt}\sum_{n\epsilon N_j}\mathrm{gn}_{nt}\right]$$

Where α_{jt} is the historical coefficient of change in prices of the fuel type j in time period t and gn_{nt} is the cumulative energy output of non-renewable generating n units in time period t (MWh).

3.1.4. Environmental factors

3.1.4.1. Emission function. Emissions can be formulated by [52] the quadratic form [53–55], addition with quadratic polynomial with exponential terms [56–58], or addition of linear equation terms [59] of generated power.

$$E_i(P_i) = \alpha_i + \beta_i P_i + \gamma_i {P_i}^2$$

$$E_i(P_i) = \alpha_i + \beta_i P_i + \gamma_i {P_i}^2 + \xi_1 \exp(\lambda \times P_i)$$

$$E_i(P_i) = \alpha_i + \beta_i P_i + \gamma_i {P_i}^2 + \xi_{1i} \exp(\lambda_1 \times P_i) + \xi_{2i} \exp(\lambda_2 \times P_i)$$

Where, α_i, β_i, $\gamma_{1i,}$ λ_1, ξ_{1i}, ξ_{2i}, and λ_2 are the emission function coefficients.

3.1.4.2. Emission of CO_2. The amount of CO_2 emission by generating units should be minimized. This objective can be determined by [48] the emission rates of the different type of generating units as follows:

$$E_t = \sum_{t\epsilon T}\sum_{n\epsilon N} E_n gn_{nt}$$

where, E_n is the amount of CO_2 emission generated by a unit of type n in time period t (ton/MWh) gn_{nt} is the cumulative energy output of non-renewable generating n units in time period t (MWh).

4. Sizing methodologies

Climatic condition plays a vital role in determining the accessibility and extent of solar and wind energy at a particular location. These data vary continuously with time. For utilizing the benefits of the solar and wind data available at a definite location, it is needed to be characterized in a specific way. The data can be used in time series or in statistical form. Table 3 explains the features associated while handling such types of data.

In recent times a large number of variables such as minimizing the total cost of the system, improving the reliability, reducing the emissions, etc. are considered while designing an HES, such as the simulation time increases enormously. This makes the selection of a suitable sizing methodology, much more important.

Various commercially available software tools for sizing of system components of HES are discussed in the paper. Among various software tools, HOMER is one of the most popular tools for sizing of HES. This tool easily finds the optimal sizing of energy systems and it is also suitable for sensitivity analysis to analyze the effects of uncertainty or change in the input variables. A list of various commercial available software tools, which are widely considered in designing of HES are presented in Table 4.

Tables 5–10 and Fig. 3 explain the various features of the sizing methodologies and how they are implemented for the sizing of HES.

4.1. Graphic construction methods

A graphical construction technique is presented by [71] for sizing a standalone PV–wind system. The technique is based on the condition that the average value of the demand must be satisfied by the average values of solar radiations and wind speed for a definite size of PV generator and wind turbine. A seasonal analysis is made for the variation of the demand and resource availability for the generators during the winter and the summer months. On the basis of analysis a sizing curve is developed between the available various sizes of wind turbines and PV generators. If the data are collected for a larger number of times then more refined curve is obtained. The paper [72] used a long-term data of solar radiation and wind speed recorded for every

Table 3
Meteorological data generation.

S No	Metrological data generation	Input	Merits	Demerits	References
1	Time series metrological data	• Weather data in hourly basis of solar radiation, wind speed and ambient temperature	• Raw data will be obtained which will explain the variability of the input parameters and accordingly design is to be made	• Location to location data is needed which is difficult to obtain of remote location	[60–66]
2	Statistical metrological data	• Weather data can generated synthetically from the monthly-average values of the meteorological data or data can also be obtained by statistical method of solar radiation and wind speed • The weather data can be extrapolated from a nearby site	• Synthetically data can be generated, which can be used when incomplete weather data is available, it will reduce the computational effort in simulation studies	• The developed system will be less sensitive to the variation of the parameters	[67–70]

Table 4
Summary of available software tools for unit sizing of hybrid energy systems.

S. No.	Software tools	Input	Output	Availibility
1	HOMER	• Load demand • Resource input • Component details including capital, maintenance and replacement cost • System control	• Optimal unit sizing • Cost of energy, net present cost • Fraction of renewable energy	Free www.homerenergy.com
2	HYBRID2	• Load demand • Resources input • Initial investment and O&M Cost of system components • Components details	• Unit sizing with cost optimization • cost of energy • Emissions in terms of percentage of various greenhouse gases • System payback periods	Free http://www.ceere.org/rerl/rerl_hybridpower.html
3	HYBRIDS	• Size of solar array • Wind turbine type • Quantity and type of battery	• Cost of energy • Percentage emission of various greenhouse gases	–
4	RET Screen	• Load data • Size of Solar Array • Required hydrology and product database • Climate database	• Energy production and savings • Costs • Emission reductions • Financial viability • Sensitivity and risk analysis	Free http://www.retscreen.net/
5	IHOGA	• Load data • Resources input data • Component and economics details	• Multi objective optimization • Cost of energy • Life cycle emission • Analysis for buy and sell of energy	PRO version is priced & EDU version is free http://www.unizar.es/rdufo/hoga-eng.htm
6	TRNSYS	• Meteorological data input of resources • Inbuilt models	• Provide the dynamic simulation results of electrical and thermal energy system	Priced http://www.trnsys.com/

Table 5
Summary of Graphic construction methods.

Reference	Study	Input parameters	Stand alone/ grid connected mode	Energy sources	Indicator optimized	Findings
[71]	Techno-economic factor	Monthly average wind speed, solar radiation	SA	PV–wind system	Power balance	• A seasonal analysis is made for the variation of demand and resource availability for the generators during the winter and the summer months. On the basis of analysis a sizing curve is developed between the available various sizes of wind turbines and PV generators. A sequence of supply-demand lines at the boundary region separated by a small time difference δt. In the limit δt-+O, the envelope of these lines will coincide with the locus of their inter-sections. We shall call the resulting curve "the sizing curve". The solution can be displayed in a convenient graphical form using the sizes of the PV and wind components as coordinates in a Cartesian plane
[72]	Techno-economic factor	Hourly wind speed and solar irradiance	SA	PV, wind generator and Battery	Cost of the system	• The average power outputs of both the wind turbine and the PV module were calculated. For a given Loss of Power Supply Probability, a different combination of the number of PV modules and the number of batteries was calculated. An optimum design choice depends on the relative costs of a PV module and a battery

hour of the day for 30 years. Load consumption of a typical house in Massachusetts was used as the load demand for the hybrid system. For a given load and a desired LPSP, the optimum configuration or number of batteries and PV modules was calculated based on the minimum cost of the system. In both the above mentioned graphical techniques only two parameters are selected (either PV–wind or PV battery). Various other factors PV module slope angle and wind turbine installation cost were not included. The above mentioned graphical construction methods are discussed in Table 5.

4.2. Probabilistic methods

The probabilistic method is one of the simplest sizing methodologies but the results thus obtained may not be suitable for finding out the best possible solution. Generally, a very few performance parameters are considered to be optimized in order to size the system. Some of the probabilistic methodologies are shown in Table 6. Continuous wind speed, solar radiation, ambient temperature, etc. data, most of the time is unavailable for a remote rural area. They must be statistically generated by insufficient data

Table 6
Summary of probabilistic methods.

Reference	Study	Input parameters	Stand alone/grid connected mode	Energy sources	Indicator optimized	Findings
[77]	Techno-economic factor	Probabilistic solar radiation and wind speed data	SA	PV, wind generator and Battery	EENS	• The model takes into consideration outages due to the primary energy fluctuations and hardware failure. The upper limit of the size of battery storage required to satisfy a given load profile is considered. A cost versus EIR for various renewable energy system configurations is compared
[78]	Techno-economic factor	Probabilistic wind speed data	SA	Diesel generator, wind generator and battery	EENS	• It is based on the modification of convolution method, which considers a given penetration level selected by the utility for stability consideration. The production costs of the Diesel units are then deduced from the expected energy not supplied (EENS) using a unit de-convolution in reverse economic order • A methodology is also presented to determine the size of the battery storage based on the excess wind energy available during operation, or that disconnected for stability consideration, while accounting for the charging/discharging cycles
[79]	Technological factor	Probabilistic solar radiation and wind speed data	SA	PV–wind and diesel generator	Loss of load expectation (LOLE)	• The paper presents a simulation method that provides objective indicators to help system planners decide on appropriate installation sites, operating policies, and selection of energy types, sizes and mixes in capacity expansion when utilizing PV and wind energy in small isolated systems • A Monte Carlo simulation approach has been utilized to incorporate the numerous random variables and their interactions
[40]	Technological factor	Probabilistic solar radiation and wind speed data	SA	PV, wind generator and Battery	LPSP	• The optimized combinations of photovoltaic modules, wind turbine and battery bank are obtained for different desired LPSPs
[80]	Technological factor	Probabilistic solar radiation and wind speed data	SA-GC	PV–wind generator	Energy index of reliability which is directly related to EENS and the internal rate of return	• The analysis of local weather data patterns shows that solar power and wind power can compensate well for one another, and can provide a good capacity factor for hybrid renewable energy applications
[81]	Technological factor	Probabilistic solar radiation and wind speed data	SA	PV–wind generator	Energy index of reliability (EIR) which is directly related to EENS and the internal rate of return	• The impact of using tracking system (one-axis, two-axis) verses fixed tilt angle on the energy performance of hybrid solar/wind system is studied. • Here the improvement of EIR using the two-axis tracking instead of one-axis tracking is marginal. The advantage of a PV tracking system is evident
[82]	Technological factor	Probabilistic wind speed data	SA	Wind generator	Wind power imbalance	• The study applies a probabilistic approach to estimate reserve requirements and establishes a methodology that makes it possible to distinguish between different categories of reserves based on the imbalance drivers of wind power • The methodology is based on sizing fast-response reserves based on the distribution of output fluctuations inside the settlement period, and sizing slow response reserves based on the distribution of the average prediction error over the settlement period

available for proper designing of HES for the locality. The reference [77] develops a renewable energy system model consisting of solar, wind and battery storage, which takes into account the outages due to energy fluctuations. A convolution method is presented in [78] which considers a given penetration level selected by the utility for stability consideration. The production costs of the Diesel units are then deduced from the expected energy not supplied (EENS) using a unit de-convolution in reverse economic order. The paper [79] presents a Monte Carlo simulation method that provides objective indicators to help system planners decide on appropriate installation sites, operating policies, and selection of energy types, sizes and mixes in capacity expansion when utilizing PV and wind energy in small isolated systems. Yang et al. [40] optimized various combinations of renewable generators for different LPSP values. A tracking system (one-axis, two-axis) versus fixed tilt angle on the energy performance of hybrid solar/wind system is studied [81]. Vos et al. [82] applies a probabilistic approach to estimate reserve requirements and establishes a methodology that makes it possible to distinguish between different categories of reserves based on the imbalance

Table 7
Summary of analytical methods.

Reference	Study	Input parameters	Stand alone/grid connected mode	Energy sources	Indicator optimized	Findings
[83]	Economic factor	Hourly solar radiation, available producer gas, discharge rate of water and biogas flow rate	SA	Diesel, biomass, biogas & PVgenerator with small hydro power plant and battery	COE	• The algorithm is capable of efficiently designing a least-cost village electrification system while the diesel generator keeps the output constant with high efficiency in spite of the fluctuating photovoltaic power • Developed algorithm is modular in nature. The time-series optimized simulation is based on detailed component modeling
[84]	Economic factor	Probabilistic solar radiation and wind speed data	SA	Wind, PV generator and battery	Production cost	• The analytical approach requires much less amount of meteorological data and also requires less time than Monte Carlo simulation
[85]	Economic factor	Hourly solar radiation, wind speed, available producer gas, discharge rate of water and biogas flow rate	GC	Coal, natural gas and hydroelectric power plants are running	COE	• The paper proposed biomass, biogas, integrated gasification combine cycle, natural gas combined cycle, solar and nuclear power station are among the new technologies that need to be considered to satisfy certain CO_2 emission reduction target. Biomass plant such as landfill gas and palm oil residue tend to become competitive at 50% CO_2 reduction target
[86]	Technological factor	Probabilistic Solar radiation and wind speed data	SA	Wind, PV generator and battery	Annual energy losses	• The data's are analyzed by the model to determine the optimal fuel mix of renewable DG units that will minimize system energy losses • There is a significant reduction in the annual energy losses for all proposed scenarios when compared to the reference scenario
[87]	Techno-Economic factor	Hourly Solar radiation, wind speed, available producer gas, discharge rate of water and biogas flow rate	SA	Wind, biomass, biogas & PVgenerator with small hydro power plant and battery	Energy Index Ratio (EIR)	• Here four different seasons are considered and accordingly the load profile is varied. The two reliability values (0.999EIR and 0.99EIR) are considered for the study
[88]	Economic factor	Hourly Solar radiation and wind speed	SA	Diesel, PV, wind generator and battery	COE	• The operation of this model was tested in two real off-grid energy systems, a cluster of villages in India and Titumate in Colombia. Both optimization processes resulted in hybrid energy systems, utilizing photovoltaics (PV), lead-acid batteries and a diesel generator as a load-balancing facility
[89]	Economic factor	Hourly Solar radiation and wind speed of previous month is used by FNN to forecast the solar radiation and wind speed for rest of the period.	SA-GC	Wind, PV generator, micro-turbine, fuel cell and battery	Total cost and total benefit	• The solution is obtained using a mixed-integer linear problem. This algorithm is implemented in AMPL (A Modeling Language for Mathematical Programming) with CPLEX (A Mixed-integer Linear Solver) and the results are double checked with another solver KNITRO • The errors associated with forecasting wind speed, PV radiation, and system load are also considered • The proposed approach employs a cost-benefit analytical technique to estimate the economic feasibility of the BESS deployment for both the grid-connected and islanded modes
[90]	Technological factor	Hourly, daily or weekly, Solar radiation and wind speed	GC	Wind, PV generator and battery	Power balancing	• The paper proposes to use discrete Fourier transform to decompose the required balancing power into different time-varying periodic components • It also introduce a cycling taxonomy (slow-cycle, intraday, intrahour, intraminute, and realtime) which relates to different operation intervals such as energy market, load following, and regulation process

Table 7 (*continued*)

Reference	Study	Input parameters	Stand alone/grid connected mode	Energy sources	Indicator optimized	Findings
						• The separation of the fast cycling components (intrahour and real-time) from the high energy capacity components requirements (slow-cycle and intraday) is another contribution of our work
[91]	Economic factor	Hourly solar radiation and wind speed	SA	Wind, PV generator and battery	Net present cost	• The result from simulation of integrated renewable system in HOMER shows that solar PV generator with battery and inverter is the most economical solution over PV–Wind with battery, to design integrated system with minimum total net present cost and cost of electricity
[93]	Economic factor	Hourly solar radiation	GC	PV generator and battery	sum of the net power purchase cost	• The objective is to minimize the cost associated with net power purchase from the electric grid and the battery capacity loss while at the same time satisfying the load and reducing the peak electricity purchase from the grid. The objective function also depends on the battery size

Table 8
Summary of iterative methods.

Reference	Study	Input parameters	Stand alone/grid connected mode	Energy sources	Indicator optimized	Findings
[45]	Economic factor	Hourly wind speed and ambient temperature	SA	Diesel generator, wind generator and Battery	Annual fuel consumption, Total cost analysis	• Estimation of optimal dimensions of the hybrid wind-diesel stand-alone system based on the minimum long-term electricity cost
[43]	Techno-economic factor	Hourly Solar radiation and wind speed	SA	PV, wind generator and Battery	LPSP, LCE	• The optimal configurations of the hybrid system are obtained in terms of different desired system reliability requirements and the LCE
[97]	Economic factor	Hourly Solar radiation, wind speed and ambient temperature	SA	PV, wind generator and Battery	Number of PV panel, Total cost analysis	• Estimation of optimal dimensions of the hybrid wind-solar stand-alone system based on the minimum long-term electricity cost
[98]	Technological factor	Hourly solar radiation, and ambient temperature	SA	PV, battery	Battery SOC	• A new iteration based on adaptive feedback learning was adopted to ensure the fast convergence of the simulation algorithm, and the simulation methodology is validated using an experimental setup
[99]	Economic factor	Hourly Solar radiation, wind speed and ambient temperature	SA-GC	PV, wind generator and Battery	System cost	• In stand-alone mode the complementary characteristics of wind and solar is fully utilized, which can achieve a smaller fluctuation of output power • In grid-connected mode the energy filter is further applied to smooth the fluctuation of power inject into the grid. Thus, the optimal size of PV/WPG/battery can not only ensure higher power supply reliability, but also ensure a much smaller fluctuation of power injected into the grid

drivers of wind power. Disadvantage of this probabilistic approach is that it cannot represent the dynamic changing performance of the hybrid system.

4.3. Analytical methods

In these methods (Table 7), hybrid energy systems are represented by means of computational models which describe the hybrid system size as a function of its feasibility. Gupta et al. [83] presents an algorithm which is capable of efficiently designing a least-cost village electrification system while the diesel generator keeps the output constant with high efficiency in spite of the fluctuating photovoltaic power. Analytical methods require less time than Monte Carlo simulation in obtaining the required size for a definite demand [84]. Patil et al. [87] considered four different seasons for sizing of the system and accordingly the load

Table 9
Summary of artificial intelligence methods.

Reference	Study	Input parameters	Stand alone/grid connected mode	Energy sources	Indicator optimized	Findings
[107]	Economic factor	Hourly mean values of wind speed, ambient temperature and solar radiation.	SA	PV, wind generator and Battery	COE	• The simulation verified that hybrid PV/wind systems result in lower system cost compared to cases where either exclusively WG or exclusively PV sources are used
[109]	Economic factor	Hourly average monthly wind speed distributions and solar radiation	SA	PV, wind generator and battery	Total system cost	• A simulation model representing a detailed hybrid energy system is completed in ARENA 12.0 software. Simulated annealing algorithm is used to optimize the model, heuristically • The performance of the optimum point of the hybrid system obtained by simulate annealing (SA) is confirmed in terms of loss of load probability and autonomy analysis on an hourly basis • The simulation model of this study can be extended in many directions by considering the inflation rate on the unit cost of auxiliary energy and other components
[110]	Economic factor	Hourly average wind speed	SA	Wind, micro-turbine and battery	Total operating cost	• Simulation results were obtained by using particle swarm optimization and were validated by sequential quadratic programming optimization. PSO-based energy management strategy has extremely fast convergence time
[111]	Economic factor	Hourly Solar radiation, wind speed and ambient temperature	SA	PV, small & large wind, diesel generator and battery	Levelized energy cost, renewable energy system penetration.	• The potential for achieving very high RES penetration levels with the introduction of BESS in an existing small island system is investigated • Parametric analysis is conducted for identifying the component's effect on objective function. This provides an indication of the range where global optimum exists, thus narrowing GA search space for faster convergence
[112]	Economic factor	Hourly Solar radiation, wind speed, ambient temperature and Steam flow rate	SA	PV, wind generator, pico hydro plant and Battery	Total cost of the system	• The optimum sizing method developed in the paper based on a Biogeography Based Optimization (BBO) • The characteristics of the main components, overall sizing, control and power management strategy for the hybrid energy system has also been presented Calculation time is reduced compared to HOMER

profile is varied. The two reliability values (0.999EIR and 0.99EIR) are considered for the study. Markov et al. [90] used discrete Fourier transform to decompose the required balancing power into different time-varying periodic components. Homer as a sizing tool for optimizing net present cost is used in [91,92]. An extensive review is presented in [94,95] of various computational simulation tools of HES.

4.4. *Iterative methods*

Performance assessment of iterative methodologies for HES is done by the recursive process which stops when the best configuration is achieved according to the design specifications. Kaldellis et al. [45] introduces an iterative process for sizing of an HES consisting of wind and diesel as sources on the basis of total cost. A model consisting of wind and PV was designed; taking into consideration the number of PV module and analysis of the overall system was undertaken in [97]. Nikhil and Subhakar [98] proposed a new iterative method based on adaptive feedback learning, which was adopted to ensure the fast convergence of the simulation algorithm, and the simulation methodology is validated using an experimental setup. Xu et al. [99] developed an algorithm suited for both stand alone and grid connected mode where an energy filter is further applied to smooth out the fluctuation of power injected into the grid. A summary of iterative methods is listed in Table 8.

4.5. *Artificial intelligence methods*

Artificial intelligence is a term that in its broadest sense would mean the ability of a machine or artefact to perform similar kinds of functions that characterize human thought. Koutoulis et al. [107] uses genetic algorithm to determine the cost of energy of the overall system and verified the use of hybrid PV/wind systems which results in lower system cost compared to cases where either exclusively WG or exclusively PV sources are used. Ekren et al. [109] used simulated annealing in ARENA 12.0 software. The performance of the optimum point of the hybrid system was obtained by taking into account the loss of load probability and autonomy analysis on an hourly basis. Particle swarm optimization (PSO) based energy management strategy has extremely fast convergence time compared to sequential quadratic programming optimization [110]. Vrettos and Papathanassiou [111] investigate the role of the battery energy storage system (BESS) in increasing the potential RES penetration levels in a small island. Bansal et al. [112,113] introduced a new algorithm biogeography based optimization (BBO) in sizing of IRES. The calculation time required by the algorithm is reduced compared to HOMER. Implementation of the

Table 10
Summary of hybrid methods.

Reference	Study	Input parameters	Stand alone/grid connected mode	Energy sources	Indicator optimized	Findings
[47]	Techno-economic and environmental factor	Hourly wind speed data	GC	Costs, environmental impact, imported fuel and fuel price risks	Conventional steam units, coal units, combined cycle modules (CC), nuclear, gas turbines (TG), wind farms, geothermal and hydro units	• In the paper, a multiobjective model for generation expansion planning (MGEP) model is presented. A framework to solve the MGEP model is proposed to obtain the nondominated solutions and utilizing Analytical Hierarchy Process (AHP) to select the "best solution" among the representative (clustered) solutions • A major obstacle is time: access to key decision makers is limited and it could be costly. A second obstacle is that there is relatively little experience with such methods in a group setting, where group members have very different priorities
[116]	Techno economic and environmental factor	Hourly wind speed, ambient temperature and solar radiation.	SA-GC	PV, Wind and Battery bank	Total system cost, energy index ratio (EIR) and emissions.	• A set of trade off solutions is obtained using the multicriteria metaheuristic method that offers many design alternatives to the decision maker
[117]	Economic and environmental factor	Hourly wind speed, ambient temperature and solar radiation.	SA	PV, Wind, Diesel, Biodiesel and Battery bank	COE and total green house gas emissions (GHG)	• A large sizes of diesel-fuelled generators lead to smaller COE and larger CO_2-eq. emissions, whereas large sizes of biodiesel-fuelled generators lead to opposite results. Furthermore, the use of FC with natural gas as a fuel is not recommended, because of their high costs and the high CO_2-eq. emissions they released
[118]	Techno-economic factor	Hourly wind speed data of past 282 days are used to forecast wind data for every hour which is generated 20 min before the start of the hour	SA	wind generator and battery	Lowest cost of battery in conjunction with large wind farm	• The paper presents sizing and control methodologies for a zinc–bromine flow battery-based energy storage system • The results show that the power flow control strategy does have a significant impact on proper sizing of the rated power and energy of the system. In particular, artificial neural network control strategies resulted in significantly lower cost energy storage systems than simplified controllers
[119]	Techno economic and environmental factor	Hourly mean values of wind speed, ambient temperature and solar radiation.	SA	PV, Wind and Fuel cell	Power loss minimization, voltage stability index, COE and emissions	• The solution obtained by the multiobjective artificial Bee colony algorithm have a good quality and better diversity of the pareto front compared to NSGA-II and MOPSO methods
[120]	Economic factor	Hourly solar radiation, wind speed, available producer gas, discharge rate of water and biogas flow rate	SA	PV, wind, diesel, biodiesel, fuel cell and battery	COE	• The hybrid simulated annealing-tabu search (SA-TS) improves the obtained solutions, in terms of quality and convergence, compared to the solutions provided by individual SA or individual TS methods
[48]	Techno-economic, socio-political and	Stochastic wind data	GC	Oil/steam, coal/ steam, hydro, wind, nuclear	Total costs, CO_2 emission, Fuel consumption, Energy price risk and minimization of outage cost (reliability)	• The study presents multiobjective generation expansion planning (MGEP) model of power electric system including renewable energy sources (RES)

Table 10 (*continued*)

Reference	Study	Input parameters	Stand alone/grid connected mode	Energy sources	Indicator optimized	Findings
	environmental factor					• The mixed-integer linear programming (MILP) is used for the proposed optimization and an efficient linearization technique is proposed to convert the non-linear reliability metrics into a set of linear expressions • Fuzzy decision maker is utilized to select the most-preferred solution among the Pareto solutions
[121]	Techno-economic factor	Hourly wind speed, solar radiation	SA	PV, Wind and Battery	Installation cost and efficiency	• Evaluates the efficiency of a hybrid system that combines renewable energy generation and energy storage to meet a controllable HVAC load
[37]	Socio-economic and environmental factor	Hourly Solar radiation, wind speed and ambient temperature	GC	PV and wind generator	Emissions reduction, estimated cost and social acceptance	• Optimal sizing of PV–WT by adopting different multicriteria decision analysis (MCDA) optimization approaches • Sensitivity of MCDA algorithms has been analyzed, by considering different weighting criteria techniques with different fluctuation scenarios of wind speed and solar radiation profiles • The proposed procedure gives decision maker the flexibility to include any kind of criteria, allowing verifying the effect of these criteria on the optimal solutions, under different input data sensitivity scenarios

artificial intelligence is complex but can provide us suitable results, helpful in designing HES. Some of the AI techniques are listed in Table 9.

4.6. Hybrid methods

Hybrid methods are an effective combination of two or more different techniques, which utilizes the positive influence of these techniques in obtaining optimal result for a specific design problem. Since most of the problems we deal with are multi-objective in nature, implementing a hybrid method is the best possible way to solve these problems which requires deep understanding of all the techniques. Meza et al. [48] present a multi-objective model for generation expansion planning (MGEP) and analytical hierarchy process (AHP) model useful in solving a multiobjective problem consisting of costs, environmental impact, imported fuel and fuel price risks. Nasiraghdam and Jadid [119] present a solution obtained by multiobjective artificial bee colony (ABC) algorithm which has a good quality and better diversity of the pareto front compared to non-dominated shorting GA-II (NSGA-II) and multiobjective PSO (MOPSO) methods. Katsigiannis et al. [120] introduce a hybrid simulated annealing-tabu search (SA-TS) which improves the obtained solutions, in terms of quality and convergence, compared to the solutions provided by an individual SA or individual TS methods. Alsayed et al. [37] determine the optimal sizing of PV–WT by adopting different multicriteria decision analysis (MCDA) optimization approaches. Sensitivity of MCDA algorithms has been analyzed, by considering different weighting criteria techniques with different fluctuation scenarios of wind speed and solar radiation profiles. As such they are complex but can provide us suitable results, helpful in designing HES. In order to present a brief summary of hybrid methods the above mentioned literature is presented in Table 10.

Each of the above mentioned techniques is summarized in Table 11, from which it can be concluded that hybrid methods provide the maximum flexibility among the other sizing methodologies. They are the most versatile, as they can resolve the limitation of a particular technique by adding some good features of other suitable techniques. This can cause a reduction in the operation time, while producing the best suitable outcome simultaneously.

5. Control and energy management

Proper control of HES with multiple RE/AE/conventional-DGs and energy storage is critical to achieve highest system reliability and operation efficiency [122]. Controller plays a vital role in monitoring and regulating the required power necessary to mitigate the load demand, a simple controller communicating with the energy source is shown in Fig. 4. Typically, a control (or energy management) system is required to determine and assign, active and reactive output power dispatch from each energy source while keeping its output voltage and frequency at the desired level. Generally, the control systems can be classified into three categories; centralized, distributed, hybrid control paradigms and multilevel control approach. In all the cases,

Table 11
Sizing methodologies and their limitations.

S. No	Sizing methodologies	Input parameters	Energy sources	Limitation	References
1	Graphic construction methods	Hourly or monthly average wind speed and Solar radiation	Few systems like PV–battery and PV–wind turbines only included	PV module slope angle and the wind turbine installation height was not included	[71,72]
2	Probabilistic methods	Probabilistic approach of sizing of solar and wind systems	Systems like solar, wind, batteries etc. are considered	Unable to represent the dynamic performance of the hybrid energy system	[73–82]
3	Analytical methods	Hourly or monthly average wind speed and Solar radiation	Systems like solar, wind, Biomass, batteries, etc. are considered, depending on the software tool used such as HOMER, RET-SCREEN etc	Less flexible in designing of the system as performance is assessed by the computational models (i.e, commercial software tools and or/ numerical approximations of system components)	[83–96]
4	Iterative methods	Hourly or monthly average wind speed and Solar radiation or Probabilistic approach of sizing of solar and wind systems	Various systems are considered such as solar, wind, batteries etc	• Suboptimal solutions are reached as the computation involves linearly changing of the decision variables • PV module slope angle and wind turbine installation height are not optimized	[45,97–99]
5	Artificial Intelligence methods	Hourly wind speed and Solar radiation or monthly average solar and wind energy values or Probabilistic approach of sizing of solar and wind systems	Various systems are considered such as solar, wind, batteries etc	Complexity in designing of the system	[100–113]
6	Hybrid methods	Hourly wind speed and Solar radiation or monthly average solar and wind energy values or Probabilistic approach of sizing of solar and wind systems	Various systems are considered such as solar, wind, batteries etc	Complexity in designing of the system	[114–121]

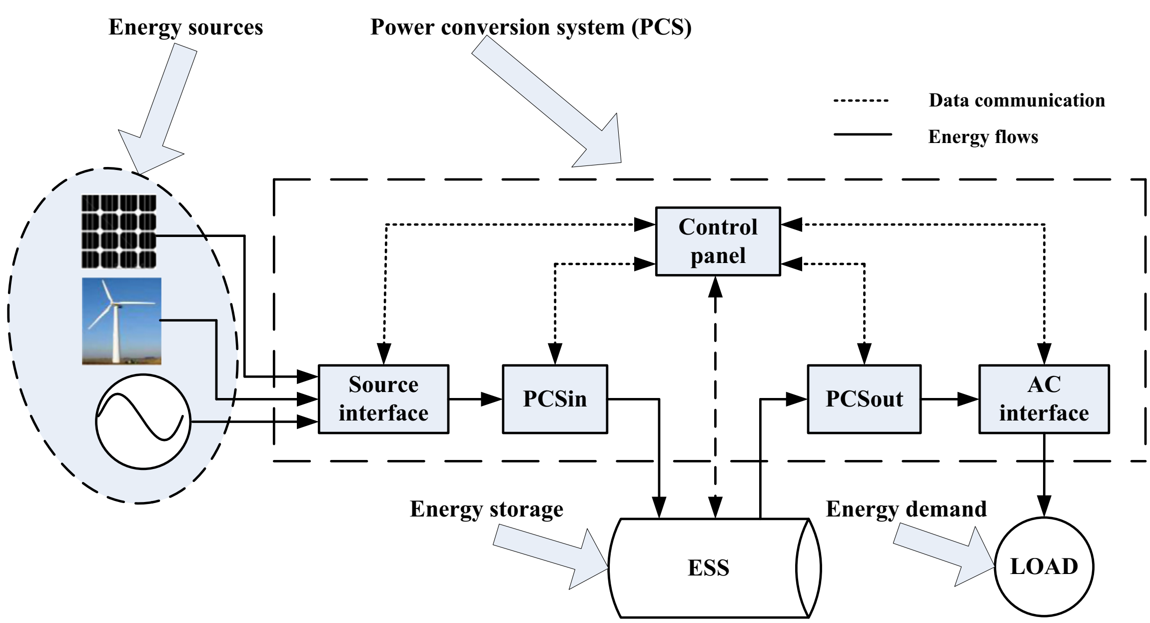

Fig. 4. Typical figure showing data communication and power flow in HES.

each energy source is assumed to have its own (local) controller that can determine optimal operation of the corresponding unit based on current information. If multiple (and at times conflicting) objectives are to be met, and all energy sources cannot operate optimally, a compromised (global optimal) operating decision may be achieved. A brief explanation of each paradigm is covered in Table 12.

6. Challenges and future scope

With the development of new technologies in the field of HES, new problems arise, which become much more intriguing to solve. These challenges must be addressed properly, to help them shorted out. The following lists some of the important challenges and scope for future research.

4.1 PV and other renewable energy sources need break-through technologies for extracting more amount of useful power. The poor efficiency of solar PV is a major obstacle in encouraging its use.
4.2 The manufacturing cost of renewable energy sources needs a significant reduction because the high capital cost leads to an increased payback time. Cost reduction will provide an incentive to the industry to implement such systems.

Table 12
Control and energy management strategies.

Control paradigm	Summary	Advantages	Drawbacks	References
Centralized control paradigm	In a centralized control paradigm, the measurement signals of all energy units in a group, i.e., a microgrid, are sent to a centralized controller	Multiobjective energy management system can achieve global optimization based on all available information	The scheme suffers from heavy computation burden and is subject to single-point failures	[123–127]
Distributed control paradigm	The measurement signals of the energy sources of the hybrid system are sent to their corresponding local controller	The computation burden of each controller is greatly reduced, and there are no single-point failure problems	Potential complexity of its communication system	[122,128–136]
Hybrid control paradigm	Local optimization is achieved via centralized control within each group, while global coordination among the different groups is achieved through distributed control	Computational burden of each controller is reduced, and single-point failure problems are mitigated	Potential complexity of its communication system	[137–139]
Multilevel control approach	Local optimization is achieved via centralized control within each group, while global coordination among the different groups is achieved through distributed control	Computational burden of each controller is reduced, and single-point failure problems are mitigated, it also consists of supervisor controller which controls the real-time operation of each energy unit, based on the control objective within millisecond range Two way communication exists among different levels to execute decisions	Potential complexity of its communication system	[139]

4.3 The losses involved in power converters have been reduced to a satisfactory level; however, it should be ensured that there is minimal amount of power loss in these converters.
4.4 The life-cycle of storage devices, such as batteries and UCs, need to be improved through innovative technologies.
4.5 With the inclusion of different generators in designing HES will increase the stress on power conversion devices. A feasible HES needs the presence of proper monitoring system, which will record important information for its successful operation. Whenever any mismatch in generation and demand exists the system will open the circuit breakers for better protection and operation.
4.6 The renewable resources are independent of the load fluctuations and hence proper energy management must be designed, so that the longevity of the HES can be improved. Large variation in the load might even lead to an entire system collapse.
4.7 The disposal of storage devices, such as batteries and other storages, is one of the major concerns for the manufacturers.
4.8 Need for the development of smart mini-grids consisting of various different generators which will interact with each other and work intelligently in delivering power according to the requirement.

7. Conclusions

The paper explains various architectures, design criterions, sizing methodologies and control paradigm of an integrated renewable/hybrid energy system. A practical HES depends on various parameters such as technological, economical, socio-political and environmental factors; for considering many of these factors while designing makes the problem intricate. It is important to select some of these factors which highly depend on the designing of HES. Computational tools such as HOMER, HYBRID2, IHOGA, RET-Screen, etc. can be used for sizing of HES or IRES. Most of the papers for sizing are carried out by using analytical techniques or tools developed by various manufacturers and artificial intelligent techniques, such as GA and PSO. BBO, ABC, AIS, etc. are some of the new AI techniques which can also be considered while sizing of HES. AI techniques are able to search complete workspace and can be programmed to converge at the best possible optimal solution, but they also sometimes become inefficient to solve certain difficulties, such as increasing the number of variables, they can be number of PV modules, no. of wind turbines or no. of batteries, etc. For overcoming the limitation of a certain sizing technique some other techniques can be blended into it for a specific problem, which can be called as hybrid methodology. Thus a set of best possible sizing of renewable/non-renewable energy system integrated to form HES can be optimized. Finally control and energy management strategies in HES are discussed in detail. Among all possible control strategies, hybrid centralized and distributed control paradigms are quite suitable and reliable in HES. In this control paradigm, local optimization is achieved via centralized control within each group, while global coordination among the different groups is achieved through distributed control.

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